The FM system

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SINCE the introduction of the 146MHz fm net frequencies to this country (Australia), many amateurs have come to realize the advantages that frequency modulation provides. However, many amateurs have only a rather sketchy knowledge of the processes involved in the frequency modulation system. It is the purpose of this article to discuss some fundamental aspects of the fm system.

Deviation

Everyone is aware of the process involved when an a.m. signal is produced. If the modulating signal is, say, 1kHz, two sidebands, one at carrier frequency minus 1kHz (lower sideband, lsb) and the other at carrier frequency plus 1kHz (upper sideband, usb) are produced. The total power in the sidebands is half the carrier power for 100 per cent modulation (see Fig 1a).

When a frequency modulated signal is produced with 1kHz modulating frequency, sidebands are produced at 1kHz intervals **to infinity** (see Fig 1b).

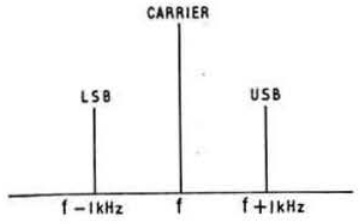

Fig 1a. AM signal with 1kHz modulation

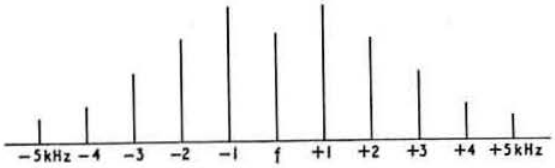

Fig 1b. FM signal with 1kHz modulation

However, beyond a certain point the amount of power contained in higher order sidebands is insignificant. The number of significant sidebands and the amount of power transmitted in them can be determined using Bessel functions. Two Bessel function charts are shown in Figs 2a and 2b.

There are several points to note with reference to Fig 1b:

(*a*) The carrier power diminishes during modulation.
(*b*) The energy taken from the carrier goes into the sidebands—greater amplitude of modulating signal produces more energy in the sidebands.
(*c*) One or more sidebands can contain **more** power than the carrier.

A small amplitude audio modulating signal of frequency 1kHz may produce sidebands as shown in Fig 3a. If the amplitude is increased, the frequency spectrum of the signal may change to that shown in Fig 3b. The signal in Fig 3b has greater deviation than that in Fig 3a.

A signal modulated with a 1kHz tone with 10 significant sidebands requires a total bandwidth of 20kHz, while a 100Hz tone giving rise to 10 significant sidebands requires a total bandwidth of 2kHz.

The bandwidth required for a signal therefore depends on:

(i) The intensity of the modulating signal.
(ii) The frequency of this signal.

The modulation index of a frequency modulated signal is defined as:

$$\text{Modulation index} = \frac{\text{Deviation of fm carrier}}{\text{Audio freq producing this deviation}}$$

For a maximum carrier shift of (±) 15kHz and a highest modulating frequency of 3kHz, the modulation index = $15 \div 3 = 5$.

From Fig 2a we see that there are eight significant sidebands in this signal, ie although the carrier has shifted only (±) 15kHz, significant sidebands have been produced to $8 \times 3 = (\pm)$ 24kHz.

The relative **amplitudes** of the sideband sets are obtained

Modulation index	Number of significant sidebands: Above carrier	Below carrier	Bandwidth required
0·01	1	1	2f
0·05	1	1	2f
0·20	1	1	2f
0·40	1	1	2f
0·50	2	2	4f
1·00	3	3	6f
4·00	7	7	14f
5·00	8	8	16f
7·00	10	10	20f
10·00	14	14	28f

Note: f equals frequency of audio signal.

Fig 2a. Bessel function chart (1)

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Modulation index	Carrier value	1st set of sidebands	2nd set	3rd set	4th set	5th set	6th set	7th set	8th set	9th set	10th set	11th set	12th set	13th set	14th set
0·00	1·000	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0·01	1·000	0·005	—	—	—	—	—	—	—	—	—	—	—	—	—
0·05	0·9994	0·025	—	—	—	—	—	—	—	—	—	—	—	—	—
0·20	0·9900	0·0995	—	—	—	—	—	—	—	—	—	—	—	—	—
1·00	0·7652	0·4401	0·1149	0·0020	—	—	—	—	—	—	—	—	—	—	—
2·00	0·2239	0·5767	0·3528	0·1289	0·0341	—	—	—	—	—	—	—	—	—	—
4·00	−0·3971	−0·0661	0·3641	0·4302	0·2811	0·1321	0·0491	0·0152	—	—	—	—	—	—	—
5·00	−0·1776	−0·3276	0·0466	0·3648	0·3912	0·2611	0·1310	0·0534	0·0184	—	—	—	—	—	—
7·00	0·3001	−0·0047	−0·3014	−0·1676	0·1578	0·3479	0·3392	0·2336	0·1280	0·0589	0·2035	—	—	—	—
10·00	−0·2459	0·0435	0·2546	0·0584	−0·2196	−0·2341	−0·0145	0·2167	0·3179	0·2919	0·2075	0·1231	0·0634	0·0290	0·0120

Note: Where blank spaces are indicated the values of the sidebands are insignificant.

Fig 2b. Bessel function (2). The -ve sign indicates that the component is 180 degrees out of phase with respect to the others

from Fig 2b and are shown in Fig 4 applied to a carrier aerial current of 9·0A.

Note that although the carrier is never shifted beyond (±) 15kHz, significant sidebands are produced beyond this limit. Hence the seemingly wide spacing between fm channels.

Note also that for a modulation index less than 0·4, only two significant sidebands are produced. A modulation index of 0·4 with an upper audio limit of 3kHz corresponds to a carrier deviation of (±) 1·2kHz (see Fig 5).

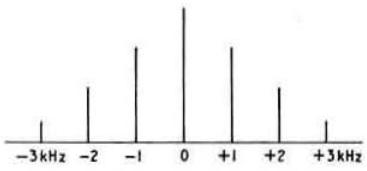

Fig 3a. Small deviation

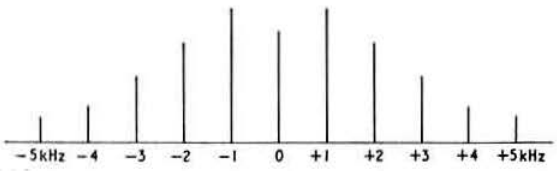

Fig 3b. Large deviation

Sideband set	Amplitude (amps)	Power (arbitrary)
Carrier	1·598	2·50
1st set	2·948	8·70
2nd	0·419	0·175
3rd	3·283	10·80
4th	3·521	12·40
5th	2·350	5·52
6th	1·179	1·39
7th	0·481	0·231
8th	0·166	0·0276

Fig 4. Power in sidebands

Phase modulation

Consider an audio signal modulating a carrier such that the phase of the carrier is changed corresponding to change in the amplitude of the modulating signal. This is shown in Fig 6a relative to a reference carrier whose phase is constant. An alternative representation in terms of rotating phasors is shown in Fig 6b where OB is the reference carrier and OA is the phase modulated signal.

Actually, in Fig 6b OA is rotating at angular frequency ω, while the phase varies, relatively, very slowly. Consider now the change in vector OA in going from (i) to (ii) and (iv) to (v) in Fig 6b. In the first case OA must speed up to go from position (1) to position (2), while in the second case OA must slow down to go from position (1) to position (3). This speeding up corresponds to an increase in frequency of the carrier represented by OA and the slowing down corresponds to a decrease in carrier frequency.

Each time the carrier phasor wobbles back and forth to reach the new phase positions dictated by the audio modulation, we find the frequency also changes in order to have the phasors reach the new positions. Note, however, that over the whole audio cycle the average frequency of the carrier represented by OA is constant.

In producing phase modulation of the carrier we have in fact produced indirect fm. What we are doing is adding sufficient change, either positive or negative, to a fixed frequency to permit the carrier to reach the desired phase position. In "pure" fm the carrier frequency itself is **directly** affected and shifted in response to the modulating voltage.

Factors affecting indirect fm

The amount of indirect fm produced depends on the extent of phase shift and the frequency of the modulating audio signal. The extent of indirect fm produced varies directly with both the frequency and maximum phase shift of the carrier.

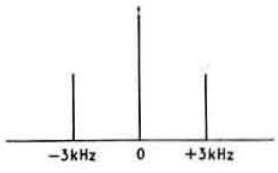

Fig 5. Small modulation index

C

In direct fm the value of the carrier itself swings between its maximum limits. The carrier is shifted directly by the modulation. In indirect fm (from pm) the carrier is not actually shifted by the modulation. Rather, the effect of the phase shifts is to either add to or subtract frequency variations from a fixed carrier.

Interference

Consider two carrier waves slightly different in amplitude and frequency. The resultant of these two waves is shown in Fig 7. There are two types of variation in this signal as compared to carrier 1. They are: (1) amplitude, (2) phase.

In a.m. systems type (1) produces beat frequencies (eg 10kHz whistle).

In fm systems type (1) is eliminated by limiters in the receiver, but type (2) is still present at the detector. Note that this phase modulation produces indirect fm. With a 2:1 ratio of desired to unwanted signals, a maximum phase shift of about 30° is produced.

The indirect fm cannot be eliminated, but in wideband fm systems it can be minimized.

As noted before, the indirect fm is directly proportional to the modulation frequency (in Hz) and the maximum phase angle (in radians) of carrier shift.

Now suppose that the interfering signal differs by 1,000Hz from the desired signal and is only half as strong as the desired signal. As noted before, a maximum phase shift of 30° (approx. 0·5 radians) in the desired signal will be produced. The frequency shift (indirect fm produced) in the desired signal is in fact 1000 × 0·5 or 500Hz. The shift is periodically above and below the average frequency of the stronger signal. The frequency variations shift at a rate of 1,000 times a second (1,000Hz mod signal).

If the desired fm signal is deviated to (±) 15kHz then the (±) 500Hz produced by the interfering signal produces an audio signal considerably smaller than the desired audio signal.

For a desired to undesired signal ratio of 10:1 this effect is even more marked. Thus the wideband fm completely swamps the small indirect fm developed from the interference. Herein lies the interference reduction power of fm.

Note that if the two signals are of the same frequency no interfering indirect fm is produced, and the greater the frequency separation of the two signals the greater the amount of interference produced. However, the amplitude will be reduced by the bandpass characteristics of the receiver.

Domination by the stronger signal

When two signals are comparable in amplitude, the moment one signal becomes even a trifle stronger the response changes and the stronger signal assumes noticeable control. The process is complete when the ratio reaches the 2:1 point. (For a comparable amount of interference in an a.m. system, a ratio of 100:1 is required.)

Consider two signals of nearly equal amplitude and only slightly different frequency (see Fig 8).

Let 1 be the stronger signal, 2 be the interfering signal and R be the resultant carrier due to these two signals. As 2

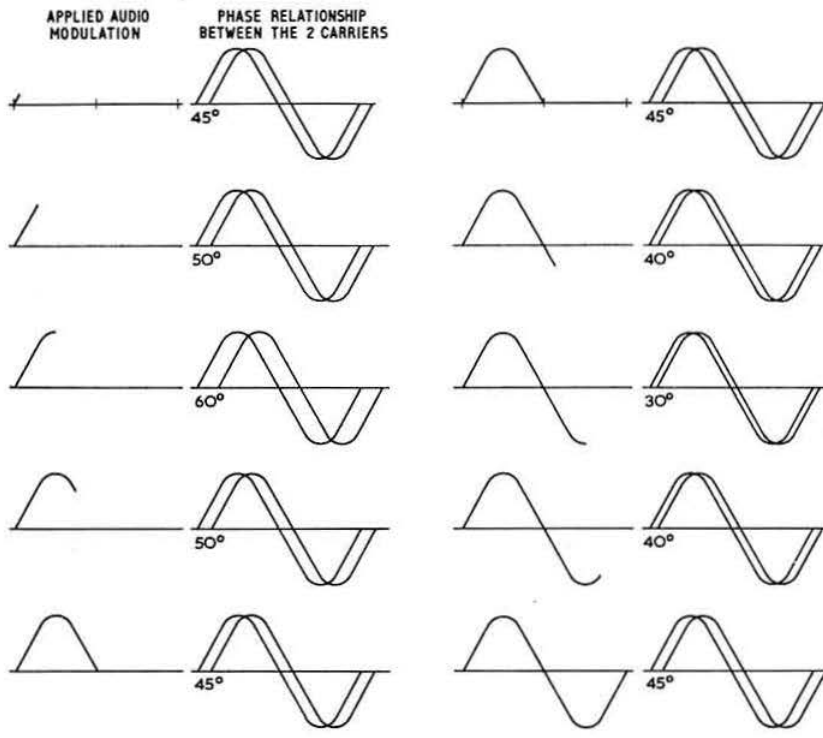

Fig 6a. A simplified illustration of phase modulation

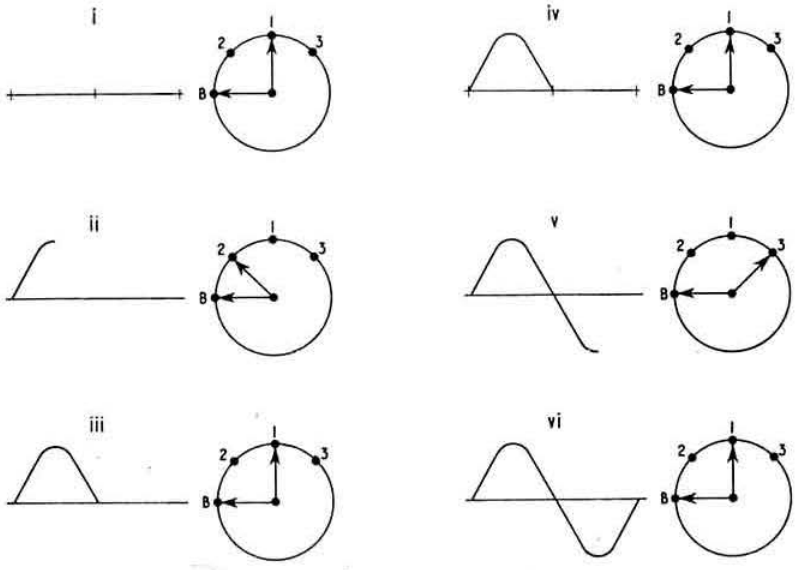

Fig 6b. An alternative representation of Fig 6a

rotates around relative to 1 (different in frequency), R changes greatly in phase but its average frequency is still that of 1, the stronger signal. Hence by bringing the two signals close in amplitude we have produced more phase modulation in the resultant phasor R, but R still follows signal 1, so we hear signal 1 but with some distortion produced by the indirect fm caused by signal 2 interacting with 1. If 2 was stronger than 1, then the phasor R would follow signal 2, hence the sharp transition from one signal to the other and this is why the predominant signal assumes control in fm systems.

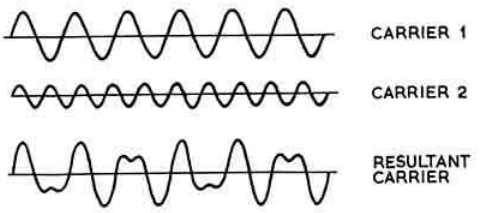

Fig 7. The combination of two carriers to form a resultant which is amplitude and phase modulated

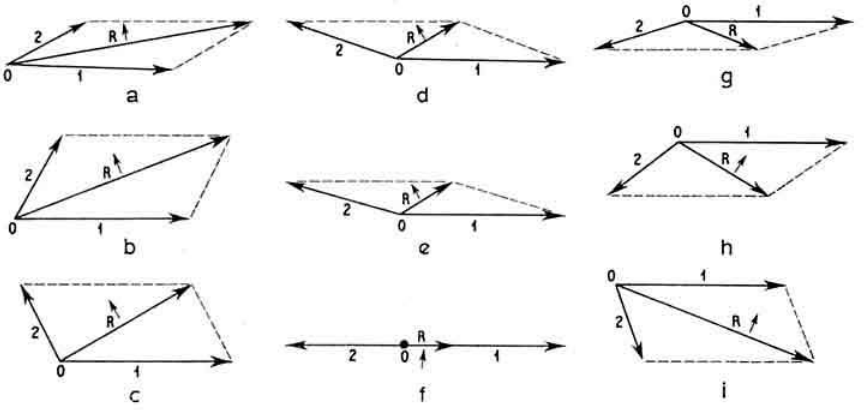

Fig 8. The amplitude and phase variation of a resultant (R) carrier due to the interaction of two signals. The small arrows on R indicate whether its phase (with respect to the desired signal, 1) is going in a positive or negative direction

Noise

Consider random noise in the receiver. Interactions between random noise voltages and the carrier, and interactions between the random noise voltages produce:

(1) Amplitude modulation of the carrier;

(2) Phase modulation (and thus indirect fm) of the carrier.

The amplitude variations are eliminated in the limiters but the phase variations (indirect fm) still result in noise.

The amount of indirect fm (ie noise) is proportional to the frequency difference between the carrier and each random noise voltage, ie zero at carrier frequency and increasing directly with increase in bandwidth (see Fig 9a). Above 5kHz we have inaudible noise (considering the response of receiver audio systems). The comparable "noise spectrum" for an a.m. system is shown in Fig 9b. Note the greater improvement in the amount of noise in the fm receiver compared to an a.m. receiver. This can be shown mathematically to be 18·75dB or an s/n voltage ratio of 8·65:1.

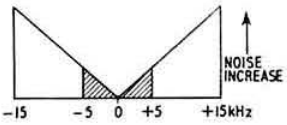

Fig 9a. Noise in fm system

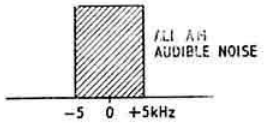

Fig 9b. Noise in a.m. system

Let us now consider the effect of reducing the modulation index of the fm system. Figs 10a to 10b to 10c show successive reductions in modulation index until in 10c, with a modulation index of 1, ie a roughly comparable bandwidth to the a.m. system, the s/n ratio improvement of fm over a.m. is 4·1875dB. Hence the importance of obtaining the highest modulation index possible.

Pre-emphasis and de-emphasis

It is well known that most of the energy of a voice-modulated transmission is contained at the lower audio frequencies, ie up to 3kHz. In addition, it has further been brought to light that the greatest irritating noise generated is located from 3kHz up. To reduce the effect of this noise, a pre-emphasis network is inserted in the audio section of the transmitter. Its purpose is to boost the frequencies above 1kHz.

At the receiver there is a de-emphasis network to reduce frequencies above 1kHz to their original values. The overall effect is a return of the signal to its proper relative proportions, but with a considerable reduction in noise.

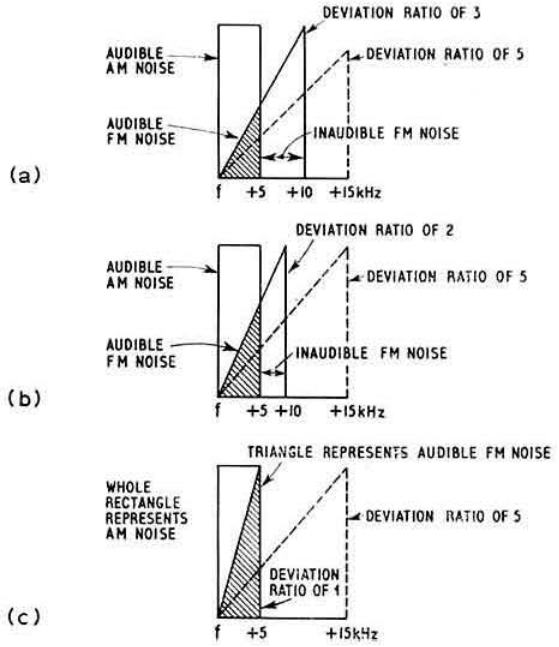

Fig 10. Further comparisons between the noise in a.m. and fm systems with various fm deviation ratios

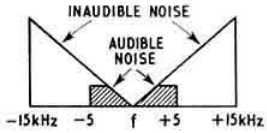

Fig 11. Improvement in noise reduction due to pre-emphasis circuit in transmitter

Another beneficial effect of de-emphasis is concerned with the noise produced by another signal or the ever-present random noise.

As previously noted, the greater the difference between the carrier frequency and the interference, the greater the indirect fm produced. By the use of the de-emphasis network the triangular response of Fig 10 is modified to the trapezium of Fig 11. The de-emphasis action, by reducing the level of all frequencies above 1kHz, slices off a considerable portion of the noise.

I trust that this article has been able to shed some light on the rather neglected subject of the theory behind the fm system and it will enable amateurs to speak with a little more authority about the effects observed in their equipment.